

Production of α -particle condensate states in heavy-ion collisions

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The fragmentation of quasi-projectiles from the nuclear reaction $^{40}\text{Ca}+^{12}\text{C}$ at 25 MeV/nucleon was used to produce excited states candidates to α -particle condensation. The experiment was performed at LNS-Catania using the CHIMERA multidetector. Accepting the emission simultaneity and equality among the α -particle kinetic energies as experimental criteria for deciding in favor of the condensate nature of an excited state, we analyze the 0_2^+ and 2_2^+ states of ^{12}C and the 0_6^+ state of ^{16}O . A sub-class of events corresponding to the direct 3α decay of the Hoyle state is isolated.

Alpha particle condensed states have been predicted to exist in self-conjugate $4N$ nuclei in the vicinity of the $N\alpha$ -decay threshold and are characterized by a low density [1–3]. Theoretical predictions agree that the most probable candidate states correspond to the Hoyle state and 2_2^+ state of ^{12}C [4, 5] and to the 0_6^+ state of ^{16}O [6]. If confirmed, these states should be regarded as the finite size replica of 4-nucleon clusterization taking place in dilute symmetric nuclear matter [7, 8].

From the experimental point of view, a candidate for α -particle condensation is a resonant state whose excitation energy is close to the $N\alpha$ threshold and which directly decays into $N\alpha$ of equal kinetic energies (in the center of mass of the emitter). Once agreed on these criteria, it comes out that, probably, the most appropriate working methodology involves full 4π detection of energetic reaction products. High angular granularity is an extra requirement for having high kinematic resolution and detection efficiency.

Data discussed in this paper have been collected in the nuclear reaction $^{40}\text{Ca}+^{12}\text{C}$ at 25 MeV per nucleon incident energy and correspond to quasi-projectile (QP) decay events. The experiment was performed at LNS-Catania (Italy), using the CHIMERA [9] multidetector. Details of the experimental settings and methods for reaction product identification and calibration may be found in Ref. [10].

The overall quality of the energy calibration was judged based on the energy evaluation of several resonant states of light nuclei inferred from two particle correlation functions ($\alpha - \alpha$, $\alpha - d$, $\alpha - t$) [10]. Taking into account the complexity of the apparatus and the fact that the maximum obtained deviation was of 20 keV, the calibration was considered reliable enough to allow for the due spectroscopic analyses.

Correlation functions are known to reveal also space-time information on the decaying source taking advantage of proximity effects induced by Coulomb repulsion and to highlight the production of event classes with specific properties. Their predictive power is now exploited in order to qualify the simultaneity/sequentiality character of a specific state decay. Let us define a generalized correlation function in terms of α -particle average kinetic energy and RMS,

$$1 + R(\langle E_\alpha \rangle, \sigma_{E_\alpha}) = \frac{Y_{corr}(\langle E_\alpha \rangle, \sigma_{E_\alpha})}{Y_{uncorr}(\langle E_\alpha \rangle, \sigma_{E_\alpha})}, \quad (1)$$

where Y_{corr} and Y_{uncorr} represent respectively the correlated and uncorrelated number of events corresponding to given values of $(\langle E_\alpha \rangle, \sigma_{E_\alpha})$, and see how does it look like for 3α decay events.

The left panel of Fig. 1 presents the intra-event correlation function corresponding to the QP events with $m_\alpha = 3$ and $7.375 \leq E_{ex} \leq 7.975$ MeV, where m_α is the alpha multiplicity and E_{ex} denotes the excitation energy of the assumed decaying state. As one may notice, around the energy of the Hoyle state above the 3α threshold two

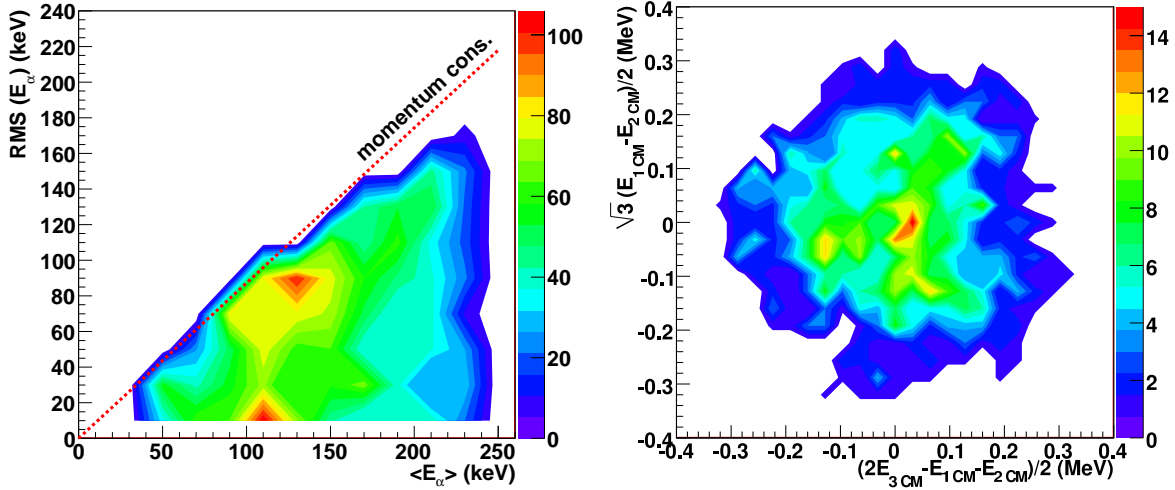


FIG. 1: Three- α intra-event correlation function (left panel) and Dalitz plot (right panel) corresponding to QP events with $m_\alpha = 3$ and $7.375 \leq E_{ex} \leq 7.975$ MeV. The uncorrelated yield is built such as to allow for decay through ^8Be . The dotted line marks the maximum RMS compatible with momentum conservation.

peaks are observed. The first one, characterized by $\langle E_\alpha \rangle = 110$ keV and $\sigma_{E_\alpha} \leq 25$ keV, corresponds, within our energy uncertainty (calibration and direction of velocity vectors), to the equal sharing of the available energy of the Hoyle state among the three α -particles. The second peak localized around $\langle E_\alpha \rangle = 130$ keV and $\sigma_{E_\alpha} \approx 90$ keV corresponds to the sharing of the available energy between the two α s of ^8Be and the remaining α of 191 keV. Numerical simulations filtered by the software replica of the detector confirm these preferential populations of the bi-dimensional event representation. Even more, in the sequential decay case, they allow us to detect the relative angle between the velocity vectors of the α s originating from ^8Be and the one of ^8Be . Thus, the extreme case in which the three α s are flying along the same direction produces a peak centered at ($\langle E_\alpha \rangle \approx 130$ keV, $\sigma_{E_\alpha} \approx 85$ keV) while the region around ($\langle E_\alpha \rangle \approx 90$ keV, $\sigma_{E_\alpha} \approx 60$ keV) is populated when the two α s of ^8Be are emitted on a direction perpendicular to the one of ^8Be .

The competition between direct and sequential decay of the Hoyle state previously reported by Freer [11] is testified also by the Dalitz plot (Fig. 1, right panel) which clearly manifests the typical pattern of each decay mechanism.

Both methods allow for an estimation of the relative probability of a sub-class of events with respect to any other. Let us focus on the particle condensation candidates. They correspond to the events localized at ($\langle E_\alpha \rangle = 110$ keV, $\sigma_{E_\alpha} \leq 25$ keV) whose number is 39. Taken into account that the total number of events with ($m_\alpha = 3$ and $7.375 \leq E_{ex} \leq 7.975$ MeV) is 1072 and the number of events with ($m_\alpha = 1$, $m_{8\text{Be}} = 1$ and $7.375 \leq E_{ex} \leq 7.975$ MeV) is 900 it comes out that 2% of the populated Hoyle states are compatible with α -particle condensation.

The same analyses may be performed in the case of the region around the 2_2^+ state at 9.6 MeV of ^{12}C . Fig. 2 illustrates the intra-event correlation function and Dalitz plot corresponding to the $1.5 \cdot 10^4$ events with $m_\alpha = 3$ and $8.9 \leq E_{ex} \leq 10.3$ MeV. The correlation function shows a broad peak which lies along the line of maximum RMS compatible with momentum conservation. The Dalitz plot manifests the symmetric three-bump structure typical for sequential decays. Out of this, it comes out that no evidence is found in favor of condensation compatible states in this case.

The intra-event correlation method, not restricted by the number of involved particles, has been applied also to 4α -events. Unfortunately, poor statistics prevents us from drawing a definite conclusion. We nevertheless mention that 4 states compatible with the above stated criteria of condensation have been identified. A dedicated experiment is planned in the near future.

To summarize, for the first time we have found experimental evidence in favor of the α -particle condensate nature of the Hoyle state of ^{12}C .

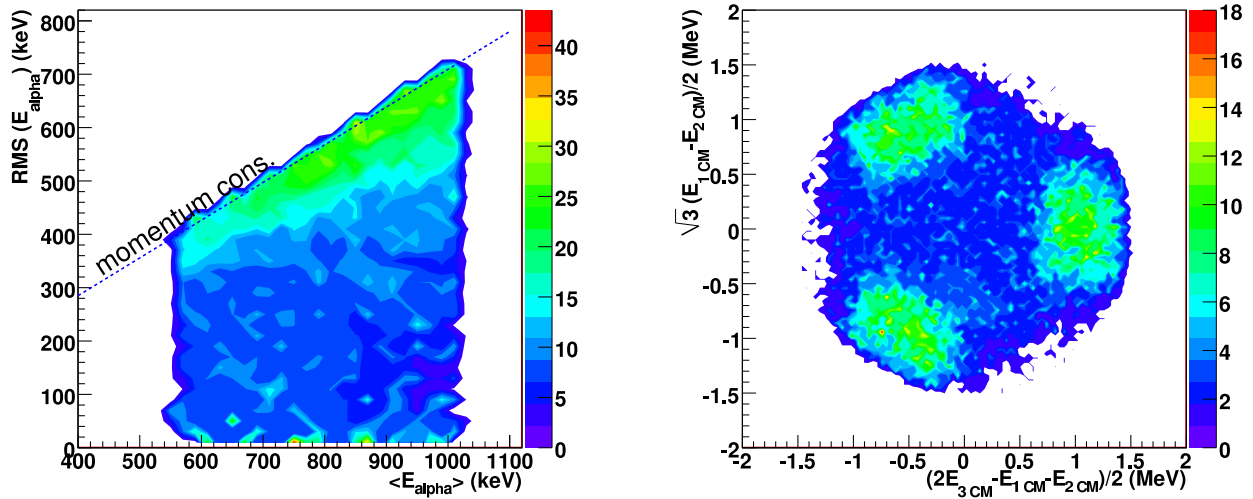


FIG. 2: Three- α intra-event correlation function (left panel) and Dalitz plot (right panel) corresponding to QP events with $m_\alpha = 3$ and $8.9 \leq E_{ex} \leq 10.3$ MeV. The uncorrelated yield is built such to allow for decay through ^8Be .

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